Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

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To cite this article: V P Budaev *et al* 2019 *J. Phys.: Conf. Ser.* **1383** 012015

Study of the stochastic clustering on the refractory material surface under the effect of plasma load in the PLM device

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Abstract. Tungsten plates were tested in stationary helium discharges in the PLM device. The duration of discharges in the PLM reached 200 minutes. A distinctive feature of this device is the stationary plasma confinement, which is advantageous for testing fusion materials, including materials of the divertor and first wall of a fusion reactor. During plasma irradiation in the PLM, the thermal load on the surface of the tested plates was more than 1 MW/m^2. The temperature of the tested plates amounted to 1000°C and more. Stochastic nanostructures with dimensions of the structural elements of less than 50 nm, including fuzz-type structures, were observed on the processed surfaces of the samples.

1. Introduction

Tests of tungsten targets, limiters, and divertor plates in modern tokamaks have shown that their surface structure considerably changes under the effect of high-power plasma load [1]. Full-scale tests of the divertor and the first wall materials are required for the ITER, as well as for the development of projects of the FNS and DEMO fusion reactors. In magnetic fusion devices, the process of plasma-surface interaction (PSI) involves several mechanisms of surface erosion, including melting and resolidification of the surface layers, melted material motion over the surface, sputtering, evaporation, redeposition of the eroded material on the surface, recrystallization, reformation of surface layers from tens of nanometers to hundreds of microns [1, 2]. The uniqueness of the PSI under conditions of high heat loads in fusion devices consists in the fact that many elementary processes can simultaneously affect the sample. As a result, the surface morphology evolution is determined by a cumulative integral effect of many elementary processes, but not by a single one of the above listed. This leads to synergistic effects considered by the theory (see, e.g. [3, 4]), which takes into account surface growth instabilities driven by stochastic motion of agglomerated particles and clusters. As a result, the structure of such a surface acquires such properties as inhomogeneous hierarchical granularity, statistical self-similarity and scale invariance of the surface structure with unusual shape; e.g., materials with cauliflower-like [1, 3, 4] and fuzz-like surfaces were recently found in fusion devices [1–5]. Speaking of the plasma-surface interaction problem, physical and chemical sputtering, thermal annealing due to plasma heat flux, material erosion and redeposition, melting, and cracking should be considered in accordance with their intensity and interrelation. For testing fusion materials, it is extremely important to ensure adequate conditions in experiments on the plasma loading of materials [1], in which the processes of changing the structure of the plasma facing surface should be investigated. For such purposes, the PLM device was constructed [6, 7]. The facility is a linear magnetic trap with a multicusp magnetic plasma confinement scheme (the 8-pole multicusp device). A distinctive feature of this device is the stationary plasma confinement, which is advantageous for testing materials of the divertor and first wall of a fusion reactor.

2. Testing of material surface under the effect of plasma load

The plasma linear multicusp (PLM) device [6, 7] is a linear plasma trap with a multicusp configuration of the magnetic field and a stationary plasma discharge that provides high-power plasma thermal load up to 5 MW/m^2 on the tested materials. The nanostructured surface formation on the refractory metals (tungsten, molybdenum, titanium and others) is studied at the facility.

The tested samples were processed with helium plasma in experiments with a discharge duration of up to 200 min. Plasma parameters measured by the Langmuir probe and the spectroscopic instruments were as follows: the plasma density was up to 3×10^{18} m^{-3}, the electron temperature was up to 4 eV (a fraction of hot electrons with a temperature of up to 50 eV was also present in plasma), the ion plasma flow onto the tested sample was up to 3×10^{21} m^{-2} s^{-1}, and the discharge current amounted to more than 15 A. The magnetic field was 0.01 T in the center and up to 0.1 T in the cusps. In these experiments, there was no active cooling of the target samples.

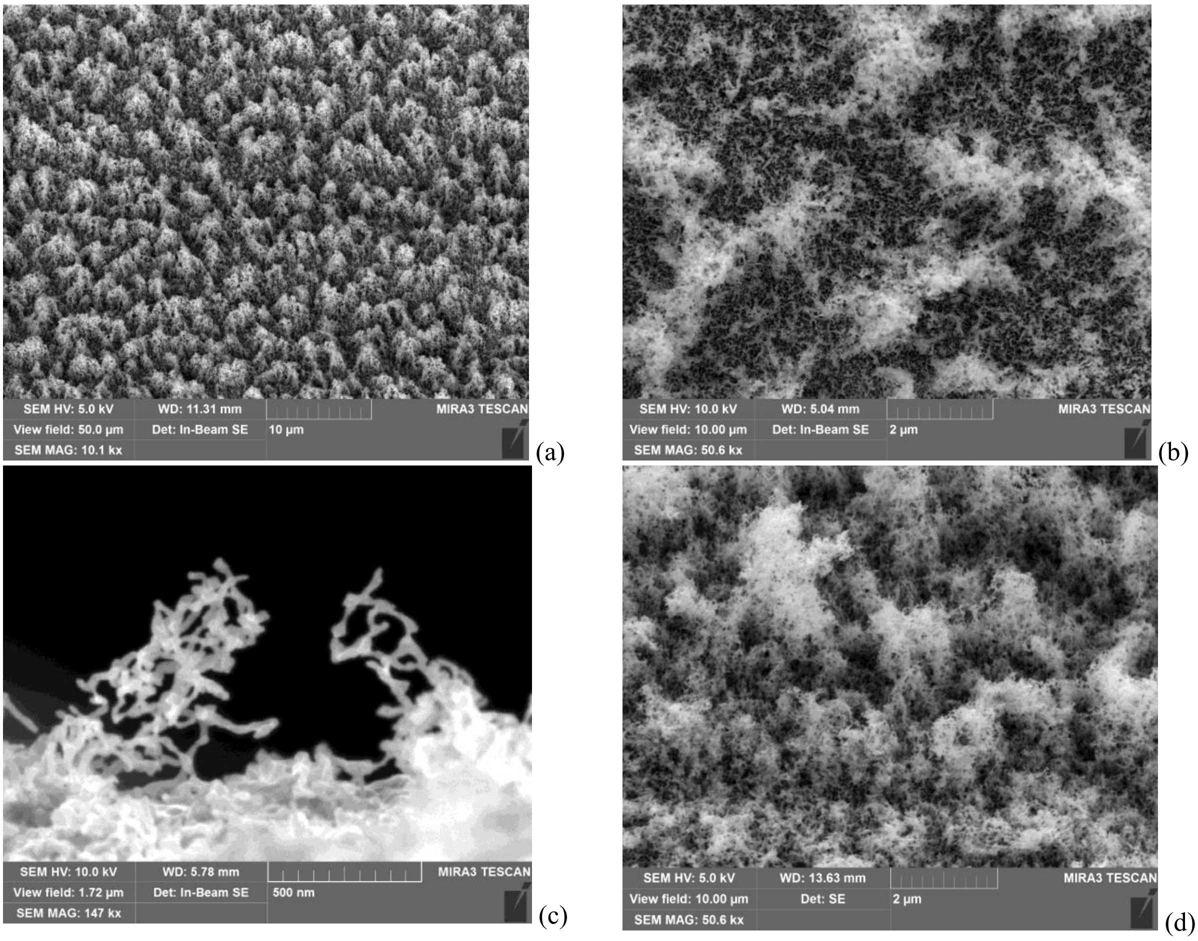


Figure 1. SEM micrographs of fuzz nanofibers on tungsten sample after processing with high-temperature plasma in the PLM device.

Journal of Physics: Conference Series **1383** (2019) 012015 doi:10.1088/1742-6596/1383/1/012015

The tungsten test samples were made from the industrial thin film and from the ITER-grade WMP "POLEMA" tungsten used for manufacturing of the ITER divertor plates. In the PLM device, the tungsten surface was processed with He^+ ions with energies of more than 40 eV; the temperature of tungsten surface was approximately 950ºC. The current flowing through the tungsten test samples with an area of 2 × 2 cm^2 reached 10 A and more. After plasma processing of the tungsten samples, fuzz-type structures on their surfaces have been detected (Figs. 1–4), including the "fuzz" (a unique type of structures), which consisted from nanofibers with diameters of 20–50 nm. The thickness of the fuzz layer was more than 1.5 microns (Fig. 2). According to the theoretical model [8], the thickness of the fuzz layer should grow with time as $t^{1/2}$.

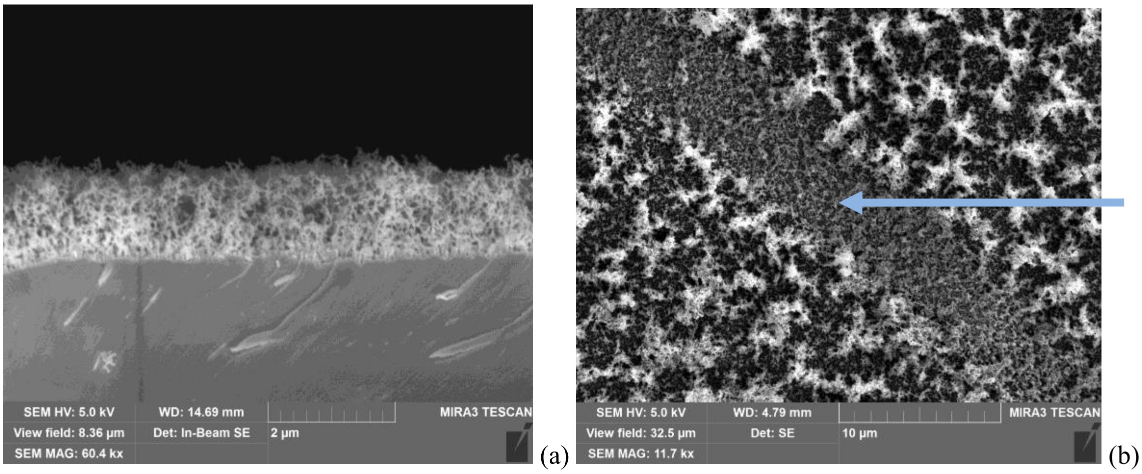


Figure 2. SEM micrographs of (a) metallographic sections of tungsten sample after processing with the high temperature plasma in the PLM device; (b) tungsten fuzz sample after mechanical testing (the surface scraping); strip of compressed fuzz layer is marked by arrow.

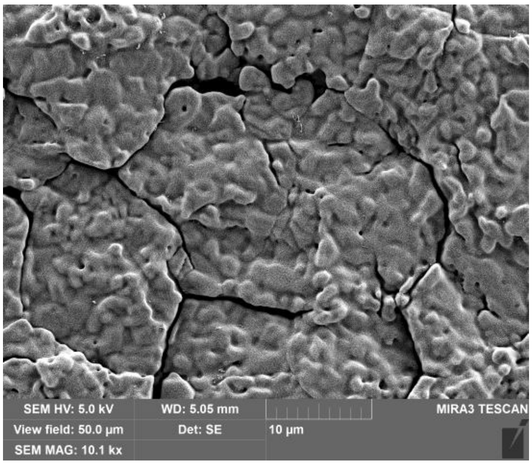
The surface of tungsten fuzzed sample was subjected to the mechanical test, Fig. 2b. Mechanical loading of the surface did not remove the fuzz layer; it was only compressed under the effect of mechanical crumbling and scraping. So, mechanical resistance of the tungsten fuzz layer is good enough.

The thermal conductivity of the fuzz layer formed on the foil target (Fig. 2a) was analyzed. The thermal conductivity of this layer is 2 times less than that of the initial tungsten foil.

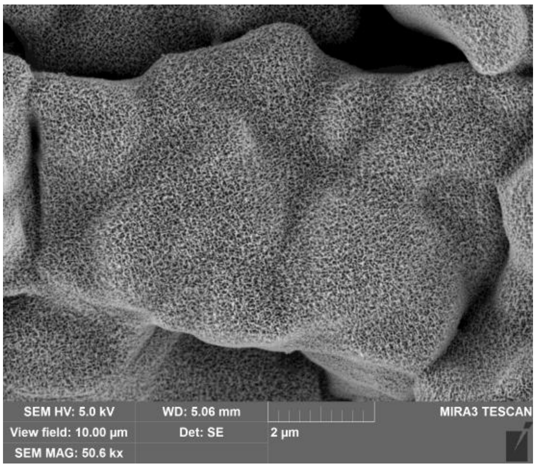
Analysis of the surfaces of tungsten samples (made of the ITER-grade tungsten) was carried out after their treatment with two stationary high-power heat fluxes: (1) processing by the electron beam providing load of 20–40 MW/m^2 (at NRU "MPEI"), and (2) further exposure of such e-beam-treated samples to the plasma load of 1 MW/m^2 in the PLM device. Basing on the SEM micrographs and X-ray analysis, it was concluded that the surface morphology of such samples considerably differs from the initial one. The electron beam load onto a tungsten surface was similar to multiple loads expected in the ITER transients (e.g. ELMs). A micro- and nanostructured surface with a large number of cracks of various scales, remelted zones and irregularly shaped clusters are formed on the target after e-beam treating providing a load of 40 MW/m^2. After plasma processing in the PLM for 200 minutes with loads of more than 1 MW/m^2, a nanostructured highly porous surface is formed on this corrugated surface: the growth of fuzz-type structures on the surface was detected, Figs. 3a, 3b.

The fuzz layers are observed over the whole corrugated surface both in the deep cracks and on the sharp hills, Fig. 3b.

The obtained results should be taken into account when analyzing the conditions for occurrence of erosion and modification of tungsten divertor plates in the ITER, where the conditions are expected to be similar to those provided during the tungsten tests by electron beam and plasma loads in the PLM device.



(a)



(b)

Figure 3. SEM micrographs of fuzz structure on corrugated ITER-grade tungsten test sample after irradiation with the high-temperature plasma in the PLM device

The fuzz surface has a large area. On such a surface, arcs can be easily ignited, which will have a strong effect on the plasma-wall interaction, including the occurrence of turbulence [9] and anomalous diffusion.

3. Conclusions

In experiments at the PLM plasma device with discharge duration of up to 200 min, tungsten samples were processed by helium plasma. In these experiments, plasma load on the tested samples amounted to 1 MW/m^2. The stochastic nanostructured surfaces and fuzz-type structures with fibers of less than 50 nm in diameter were observed on the tungsten plates processed by hot plasma in the PLM. Refractory metals with the high-porosity nanostructured and fuzz-like surfaces are in demand for operation in fusion reactors under conditions of extreme thermal and plasma-beam loads, covering the streamlined surfaces of aircrafts in order to reduce the aerodynamic drag at supersonic and hypersonic speeds, as well as for the biomedical applications.

Acknowledgments

The work was supported by the Russian Science Foundation (project no. 17-19-01469); the ASNI construction on the PLM was supported by the RF Megagrant no. 14.Z50.31.0042.

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